

# **FINAL REPORT**

**Support to 2<sup>ND</sup> Generation RLV propulsion Project Office**

**Reference: Purchase Order # H-34351D Mod #2**

Lee & Associates, LLC

March 7, 2002

Reference: P.O. # H-34351D Mod #2

## **Introduction**

The Primary activities of Lee & Associates, LLC per the referenced Purchase Order SOW for this reporting period has been in direct support of the 2<sup>nd</sup> Generation Propulsion Projects office. Independent oversight, evaluation, and/or assessment of propulsion technical and management topics, areas, and problems which were assigned by the RS-83 and COBRA Project representatives.

## **Tasks**

The objectives of this effort were accomplished during the months of October 2001 through February 2002 by Mr. Otto Goetz. The tasks included:

1. Participated in the COBRA Turbomachinery Systems Requirements Review (SRR), prepared RIDs and reviewed RID dispositions. 10/1/01
2. Participated in the COBRA Valves and Actuator SRR. 10/10/01
3. Participated in the COBRA Systems Requirements RID Review. 10/15/01
4. Participated in the COBRA Channel Nozzle Review. 11/4/01
5. Reviewed and provided comments to the "SLI Engines Proposed Structural Requirements" document. 11/15/01
6. Participated in the RS-83 Engine Quarterly Review. 12/13/01
7. Participated in the COBRA Nozzle PDR. 12/18/01
8. Participated in the COBRA Prototype Preburner PDR. 12/19/01
9. Participated in the COBRA Prototype Engine Valve and Actuator Requirements Review. 1/17/02
10. Participated in the COBRA Engine Health Management System Requirements Review (EHMS) 1/23/02
11. Participated in the COBRA Powerball Preliminary Design Review(PDR) 1/23/02
12. Participated in the COBRA Critical Design Review for the Subscale Main Combustion Chamber. 2/7/02

All data and information resulting from the individual efforts were made available to Engine Project representatives in real time during the various reviews in order that timely action by the Project Office could be taken. In addition a summary of the comments and observations resulting from the November 2001 through January 2002 are attached. The comments and observations resulting from the October reviews were presented in the Interim Report #1 submitted on November 11, 2001.

## **Attachments**

- Attachment #1 – RS – 83 Engine Quarterly Review
- Attachment #2 – COBRA nozzle Preliminary Design Concept Review
- Attachment #3 – COBRA Prototype Preburner Preliminary Design Review
- Attachment #4 – COBRA Prototype Engine Valves and Actuators SRR
- Attachment #5 – COBRA Prototype Engine Health Management System SRR
- Attachment #6 – COBRA Prototype Powerball PDR
- Attachment #7 – Comments to the SLI Proposed Structural Requirements document

## ATTACHMENT #1

To: Mr. Jack Lee  
Lee & Associates LLC  
New Market, AL

From: Otto K. Goetz  
Consultant

Subject: Summary of Notes and Observations on The December 13, 2001,  
**RS 83 Engine Quarterly Review**

Date: January 6, 2002

The RS 83 Engine Quarterly Review was conducted via Telecon at MSFC on December 13, 2001, with Rocketdyne presenting.

Rocketdyne presented a comprehensive management and engineering status report with emphasis on areas where detailed trade studies are presently being performed. The major open areas are:

- the Low Pressure Oxidizer Pump turbine drive
- the engine control logic
- the engine area ratio
- the MOV throttle concept
- the use of two PB hot gas throttle valves

The RS 83 Engine Chief Engineer presented the following "watch list":

- Parameter optimization
- Component trade studies
- Transient Model
- Health monitoring system and related instrumentation
- Need for and design of the acoustic cavities
- Fabrication of the Main Combustion Chamber
- Main Injector element definition
- Engine Control logic

Rocketdyne has generated an exhaustive presentation on SSME lessons learned and is making an all out effort to avoid a repeat of those problems on the RS 83 Engine.

A very helpful tool Rocketdyne is using in the assignment of a Technology Readiness Level (TRL) to decision areas like designs, material selections, flow schemes, heat transfer issues, etc.

Numerous engine configurations in regard to turbopumps/preburners/hot gas manifold/ducts were studied, and the candidates were narrowed down to three configurations of which the "three Bowl", and the " External Crossover" configuration were favored.

Page 2 (RS 83 Engine)

In order to meet the Main Combustion Chamber life requirement of 100 cycles (times 4), Rocketdyne is proposing to coat the inside of the MCC with an insulator like Zirconium Oxide. Concerns were expressed as to the adherence of the coating over the life of the chamber, and the effects in case of coating loss upon chamber life and engine balance. If coating loss is unacceptable, field repair techniques will have to be developed.

The proposed nozzle for the RS 83 engine is a truss wall construction and it will likely be procured from Volvo.

## ATTACHMENT #2

To: Mr. Jack Lee  
Lee & Associates LLC  
New Market, AL

From: Otto K. Goetz  
Consultant

Subject: Summary of Comments and Observations on the December 18, 2001,  
Preliminary Design Concept Review Telecon at MSFC for the **COBRA  
Nozzle**

Date: January 4, 2002

Aerojet presented a well organized approach to the nozzle design and the manufacturing feasibilities with serious consideration to cost. Aerojet delineated what they know, what the options are and what data they still need in order to make sound design and manufacturing approach decisions.

The planned approach is to build a subscale nozzle, 2 prototype nozzles and the full scale nozzles. The assumptions that went into the cost models were that 100 flight nozzles would be procured with a production rate of 12 nozzles per year. Even though the number of engines per 2nd Gen Vehicle is still open, Aerojet assumed 3 engines per vehicle in their studies.

The basic nozzle design is a channel wall nozzle not unlike the Russian nozzles, especially the nozzle of the RD O120 LH2/Lox engine.

The major open issues as presented are:

- 1) The design and manufacturing of the inner liner
  - a) spinning or rolling
  - b) coolant flow concepts, channel arrangement, coolant flow direction, hot gas side wall thickness
  - c) machining of coolant channels with attendant feasibility to meet tolerance requirements, especially hot gas side wall thickness
  - d) material selection
- 2) The manufacturing and joining of the outer shell to the inner liner
  - a) forming and machining of the outer shell
  - b) explosive forming of the inner shell into the outer shell or precision machining of both shells
  - c) application of braze material

Aerojet presented a comprehensive approach to address the potential of combustion instability. The most stable injector design will be selected during the Photo-sub-subscale preburner bomb or pulse tests of three basic injector patterns. The approach of using the photo-subscale hardware was discussed extensively and was agreed to by the MSFC stability experts.

Aerojet still plans to have propellant filters designed into the injector. The requirement for these filters is not clear since the propellants will meet the cleanliness specification and upstream engine hardware should be designed and build not to shed any parts. No plans were presented as to periodic inspection requirements for contamination of these filters during the service life. The filters are designed to have low delta p's and should not appreciably affect the engine balance.

The temperature spike during transients cannot be addressed during testing of the photo-subscale preburner, nor will it be addressed during the prototype preburner only tests due to the difficulty to simulate engine transients with a pressure fed facility setup. Only the bootstrapped Powerhead tests at P7W and the engine tests at SSC will allow the development of start and shutdown sequences that have temperature spikes and temperature gradients that are tolerable by the downstream turbomachinery hardware. Neither the acceptable spike peaks nor the acceptable temperature gradients have been determined by P & W turbomachinery and been given to Aerojet.

The decision to have a prototype preburner with flanges is still open. The major downside being its weight. In addition, Aerojet has not established any structural criteria in regard to acceptable factors of safety due to flange angularity, offset and displacement, nor do they design the prototype Preburner with a factor of safety for flange separation.

Aerojet intends to conduct a Systems Safety Hazard Analysis (SSHA), however the groundrules for hazard identification and acceptability have not yet been established.

The preburner verification requirements to be accomplished by the prototype testing have not been clearly defined. It would help to have a matrix of requirements and their verification methodology for the photo-subscale tests, the prototype tests and the full scale tests.

## ATTACHMENT #3

To: Mr. Lack Lee  
Lee & Associates LLC  
New Market, AL

From: Otto K. Goetz  
Consultant

Subject: Summary of Comments and Observations on the December 19, 2001,  
PDR at MSFC of the **COBRA Prototype Preburner**

Date: January 5, 2002

Aerojet conducted the Preliminary Design Review of the Prototype Preburner at MSFC on December 19, 2001.

The nominal Preburner design parameters used by Aerojet were:

$P_c = 5000$  psi

$MR = 0.776$

Temperature =  $1450^{\circ}R$

Aerojet plans to build 2 Prototype Preburners, one for the Preburner only tests and one for the Powerhead tests at Pratt & Whitney. No third back-up unit is planned in case of an incident.

Aerojet was well prepared and addressed a list of historical SSME Preburner problems in the COBRA Preburner design and manufacturing approach. The SSME problems taken into account were:

- Lox post cracking due to HCF
- Non-concentric Lox posts
- temperature striations during mainstage
- transient temperature spikes
- fuel baffle contamination
- interpropellant leakage
- ASI orifice problems
- ignition problems

The major open challenges in the Preburner design are:

- combustion stability
- requirement of combustion chamber coolant
- ice formation at low thrust levels
- Prototype PB weight (presently very overweight)
- temperature uniformity and its demonstration
- Ignition system



Aerojet has selected A286 as the liner material, however, they are also considering Zirconium Copper. With the present engine balance, the A286 liner requires a thermal protection coating in order to meet the engine life requirement of 100 cycles with a factor of 4. Zirconium Copper with its high heat conductivity does not require any protective thermal coating.

Recommendations:

A) The prototype nozzle should have the same materials and should be manufactured as close as possible like the full size flight configured nozzle. The presently planned subscale nozzle already deviates substantially from the prototype nozzle in design, material selection and manufacturing, and therefore some technology gains acquired with the subscale nozzle may not be applicable to the larger scales due to its differences.

B) Coatings do not always adhere to the base material and flake off. Aerojet has not addressed the loss of coating in the nozzle and its effect on engine balance during a flight. Coating repair during the service life of the nozzle was not addressed nor was the effect of loss of coating on engine life. on nozzle life.

C) The reliability of the channel wall nozzle is very much dependent on the manufacturing process. It is suggested that the Cobra project performs a FEMA of the nozzle manufacturing process similar to the very successful Process FEMA that Thiokol conducted for the manufacturing of SRMs.

D) Hot gas side wall nozzle leaks potentially caused by FODs and the effect on engine balance and redlines and/or health monitoring have not been studied, nor is it known what nozzle leak size the engine could tolerate in regard to some component life like turbine blades.

## ATTACHMENT #4

To: Mr. Jack Lee  
Lee & Associates LLC  
New Market, AL

From: Otto K. Goetz  
Consultant

Subject: Summary of Notes and Observations on the January 17, 2002  
Systems Requirements Review Telecon at MSFC for the COBRA  
Prototype Engine Valves and Actuators.

Date: January 28, 2002

Pratt & Whitney presented the Systems Requirements Review for the Prototype Engine Valves and Actuators. The valves and their actuators covered in the review were:

Main Fuel Valve	MFV
Preburner Fuel Valve	PFV
Preburner Oxidizer Valve	POV
Oxidizer Bypass Valve	OBV
Fuel Bypass Valve	FBV
Main Oxidizer Valve	MOV
Coolant Control Valve	CCV
Fuel Inlet Valves	FIV
Oxidizer Inlet Valves	OIV

The FPV, OPV, MOV and CCV are throttlable for thrust and mixture ratio control. The requirements for the propellant inlet valves (FIV & OIV) are not completely defined since these valves are not required for the prototype engine and since they also interface with the vehicle.

Major Comments:

- Some uncertainty existed as to which internal pressures are to be used for the design of the valves. It was determined in the meeting that the operating pressure plus 20% is to be used for the structural design, while the Maximum Expected Operating Pressure (MEOP) is to be used for life cycle determination.
- Considerable discussion time was spent on the weight requirement for the prototype valves and the comparison to the weights of the FSD valves. It was decided not to finesse the weight of the prototype valves in order to save cost and manpower.
- The throttlable MOV is planned to be a butterfly valve which may be a risky application for a butterfly due to high torque, flow separation and attendant vibrations.

## Page 2 (Valves & Actuators SRR)

- The valve position requirements in the non-operating engine modes like during transportation, etc. has not been addressed. It is not clear how a required closed position is assured in all operational phases by using EMA actuators, especially when no electrical power is available.
- The Prototype Engine does not have a control system requirement to fail operationally (Fail-OP). It is not evident that a Fail-Safe mode is required for the prototype engine. No implementation scheme was presented should a Fail-Safe system be required..
- The MOV is spring loaded closed with approximately 2500 in-lbs torque. The maximum operational flow torque is estimated to be ~ 4800 in-lbs for a total actuator torque requirement in excess of ~ 7300 in-lbs. This torque is rather high for an EMA actuator and may be outside the MEA experience base.
- It is unclear to what operational phase the stated internal valve leakage requirements apply. The stated leakage requirements should be tied to an operational event, like at the end of each flight, prior to each start, prior to every X start or at the end of the specified engine life. The method to be used to determine internal valve leakage has not been selected. In addition, are the prototype leakage requirements equal to the FSD requirements?
- No requirement was identified in regard to EMA interface or valve shaft seal overboard leakage.
- The LRU requirement for each of the 9 valves and actuators was not addressed. It appears that even for the prototype application easy field replacement capability is very desirable.
- The sensitivity of the EMA actuators to chill-down time has not been evaluated. There may be a potential limit should the actuator get too cold.

## ATTACHMENT #5

To: Mr. Jack Lee  
Lee & Associates LLC  
New Market, AL

From: Otto K. Goetz  
Consultant

Subject: Summary of Notes and Observations on the January 23, 2002, **Systems Requirements Review (SRR) Telecon at MSFC for the COBRA Prototype Engine Health Management System (EHMS)**

Date: January 29, 2002

Pratt & Whitney presented a well prepared and very detailed approach to the development of 3 sensors to be used in the EHMS. The sensors addressed in detail were the Turbine Blade Temperature Sensor (TBT), the Real-Time Vibration Sensor (RTV), and the Acoustic Bearing Sensor (AB). In addition, P & W presented a preliminary approach to the Plume Sensor Concept. OPAD was included in the various DRD requirements paragraphs, however, it was not addressed in detail and referred to as potential facility instrument.

General Comments:

1) P & W did not address the System Requirements for the Health Monitoring System, but only addressed the 3 sensors individually as to requirements, verification, trades, development, risk reduction and schedules. No control logic tie-in with the engine control system (Pc, pressures, pump speeds, flows, temperatures) or the physical interface with the engine controller was presented. Since this was a SRR for the prototype EHMS, and since the FSD controller architecture and the vehicle are not yet defined, P & W restricted the presented effort to the sensors that require further development.

2) The sensor requirements were confined to the mainstay operating parameters and the other attendant engine operating phases, like

Launch Commit  
Engine Ready  
Start Confirm before Lift-off  
Mainstage  
Shutdown and post Shutdown  
Maintenance Monitoring post Flight

were not considered.

3) The differences between requirements for the prototype engine and the full scale engine as to sensor operation and control logic were not delineated..

4) The ICDs for the FSD vehicle interface or facility interface for the prototype engine EHMS in terms of control logic and physical interface like power supply, data recording, etc. have not yet been generated. The prototype testing will require a vehicle simulator whose requirements to support the EHMS sensor development and the other instrumentation and controls still needs definition.

5) A logic or strategy for the EHMS self-monitoring of declaring sensors and their output valid or disqualified was not presented.

6) The requirement for redundant sensors due to high engine reliability requirements and historically lower sensor reliability has not been analyzed. Paragraph 3.2.11 states that the EHMS shall be designed to detect its own internal software errors and hardware faults. However, the reaction logic to these errors and failures was not addressed.

## ATTACHMENT # 6

To: Mr. Jack Lee  
Lee & Associates LLC  
New Market, AL

From: Otto K. Goetz  
Consultant

Subject: Summary of Notes and Observations on the January 24, 2002, Preliminary Design Review (PDR) of the COBRA Prototype Powerball held at MSFC via Video-Teleconference

Date: February 2, 2002

Aerojet presented the preliminary design of the powerball which is the strongback of the engine that connects the single preburner to the turbopump turbines and in turn collects and ducts the turbine exhausts into the main injector. Plans are to manufacture 3 prototype powerballs, one to be cut up for manufacturing verification, one for hot fire tests, and one as a spare. The powerball consists of two major structures, an outer shell that collects the turbine exhaust gases and contains the general pressure, and an inner so-called Y-duct into which the preburner fires and which directs the hot gases to the fuel and oxidizer pump turbines.

Major Comments:

1) It was reported that the engine thrust cannot be conducted through the powerball since the powerball would deform beyond what the turbopumps could tolerate. Therefore, a separate thrust structure from the main combustion chamber to the gimbal bearing (which is now not attached to the powerball) will have to be designed. This TBD thrust structure was not part of the PDR.

2) Considerable discussion time was spent on the question as to whether a feature should be designed into the Y-duct such that it will fail "preferentially" and thereby providing in case of an incident, a hot gas bypass around the turbines thereby taking the power out of the pumps. The decision to implement such a feature requires further and more in-depth study to assure that no additional undesirable failure modes are introduced by this "preferentially fail" design.

3) The Y-duct is nestled into the outer shell by two pins, one fitting into the top of the outer shell, the other fitting into the Hot gas diffuser which bolts onto the bottom of the outer shell. At present, the pins have very loose tolerances and the idea is that the turbine interfaces will center the Y-duct. The turbines do not have any bellows and it is not clear how they can center and retain the Y-duct in position without spring loading it to compensate for thermal deformations. It appeared that the Y-duct could easily "rattle" during mainstage operation. It was suggested that, as a minimum, a tolerance stack-up

analysis be performed to assure that this duct is firmly in place during the operational phases. Otherwise, alternate design solutions for the firm retention of the Y-duct should be studied.

4) The prototype powerball is considerably overweight, however, the weight becomes much more critical for the FSD engine.

Presentation: SLI Engines Proposed Structural Requirements dated Sept 22, 2001

Presenters: Rene Ortega, Pravin Aggarwal, Wayne Gregg

Comments from Otto Goetz:

Written down by Kathryn Kynard

These were written down during a phone conversation – to get clarity please contact Otto (256-828-3411). I hope that I have written down Otto's comments accurately. Otto's notes are based on the original presentation sent to him. If there have been changes to it ie: typo's etc. they are not taken into account here.

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Page 7:

*Comment:* "A" Basis is unrealistic. It is normally done for normal stress – not for fatigue and mechanics. It increases the cost of the program, tremendously. "A" Basis requires a lot of data points. I am in disagreement with this point because it is not realistic.

Page 8:

*Comment:* Question: S.F. Yield 2.0 – Weight will go up – this is not realistic trade between factor of safety and weight.

Page 10:

*Comment:* I'm in agreement with stress/strain of 1.15 in determining HCF. I'm in disagreement with the second bullet putting a factor of safety on top of a factor of safety. It should be 1.15 and nothing else. 10 is unrealistic. I recommend nothing but if there has to be something, 4 is better.

Page 11:

*Comment:* Stress Concentrations – what needs to be done is to avoid all of these in manufacturing. Need to control and not take care of stress analysis with safety factors. Don't pile safety factors on safety factors to eliminate them (*stress concentrations*).

Page 12:

*Comment:* "Don't fly any cracks" – In some cases it is unavoidable. Interpropellant cracks are being flown in SSME main injector. You can fly cracks.

Life Management.